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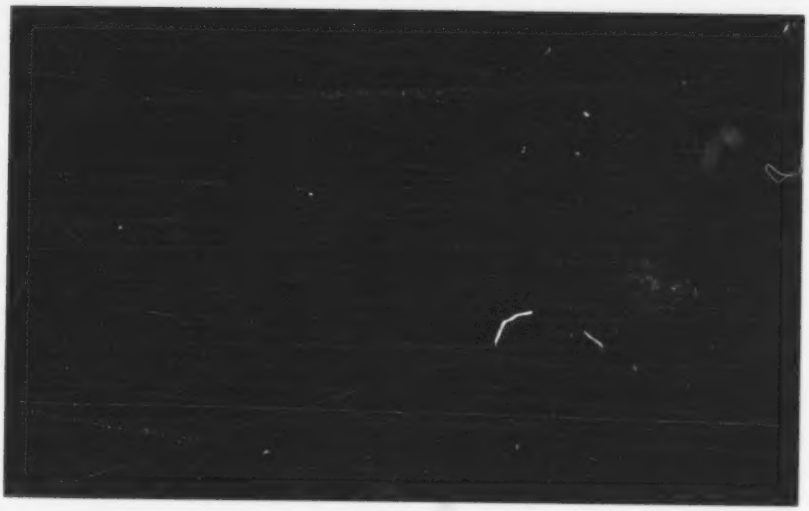

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A KNOWLEDGE BASED INTERPRETATION SYSTEM OF DYNAFLECT DATA

by

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RÉSUMÉ

Cet article présente la méthodologie qui a été utilisée pour constituer la base de connaissances d'un système expert. Ce système vise à l'interprétation sur place des résultats produits par des machines Dynaflect qui sont employées pour l'évaluation de la capacité structurale des chaussées.

Cette méthodologie combine deux approches distinctes: la première, quantitative, est bien connue et largement utilisée, alors que la seconde est de nature qualitative. Celle-ci se base sur l'expérience passée, sur l'information visuelle disponible sur place et sur des techniques de traitement des connaissances pour déduire, dans les cas où la première méthode ne peut fournir des résultats précis, un ensemble de configurations possibles de la structure de la route et une évaluation structurale globale qui constitue une synthèse de ces configurations.

Mots clefs: évaluation de la capacité structurale des chaussées, systèmes experts.

ABSTRACT

This paper presents a methodology which has been used to set up the knowledge base of an expert system. This system is intended to help in the on the spot interpretation of the results produced by Dynaflect machines which are used for the assessment of the structural capacity of pavements. Two methods are combined, the first one is quantitative, well known, and widely used, the second one is qualitative. It makes use of past experiments, on site visual information and knowledge techniques to derive, in the cases where the preceding method fails to give accurate results, a set of possible configurations of the road structure and then a global structural evaluation of the pavement which can be seen as a summary of all these configurations.

Key-words: structural evaluation of pavement, expert systems.

Nondestructive testing for structural evaluation of pavements is a commonly widely used technique nowadays. A nondestructive test can easily be done in a little amount of time with devices such as the Benkelman Beam, the Lacroix deflectograph, the Falling Weight Deflectometer or the Dynaflect. With the measures given by most of these devices it is possible to determine the shape of the deflection basin which can be considered as a good indicator for the structural capacity and structure of the pavement. The research presented in this paper is devoted to the interpretation of Dynaflect results.

1. INTRODUCTION

The Dynaflect is a widely used instrument to measure the capacity of a road to support traffic load. A sampling with this device consists in recording the effect of the impulses applied by a vibrating load located through two steel wheels. This effect is measured by five sensors (geophones). The first one is located between the two wheels, the others are spaced 30 cm apart from each other on the same axis. The value given by the first geophone depends on the characteristics of the whole pavement. The characteristics of the soil can be derived from the measure given by the geophone located far from the load (g_5). The characteristics of the subbase and the base can be obtained from the measures given in intermediate points (g_3 and g_4) while the characteristics of the upper layers are related to the measure given by the two first geophones (g_1 and g_2).

Previous studies (1,2,3,4,5) have shown that the Dynaflect was able to predict the structural quality of the pavements. Most prediction methods are of empirical nature and are based on indexes such as the maximum Dynaflect deflection (DMD), the surface curvature index (SCI), the base curvature index (BCI) or the spreadability (SP). Classifying systems ("classifiers") have been developed using these indexes. They are currently used but only give good results in the cases of road and soil conditions similar to these encountered in the sample used for their design. In other

methods the deflection basin is used to predict the elastic properties of the soil and the layers of the pavement. The thicknesses of the layers are supposed to be known as well as the Poisson's ratios and the Young's moduli are calculated accordingly. The application of these methods which give a useful information on the pavement and the soil can however lead to severe misinterpretation when the hypotheses they depend on are not verified (1). This situation may occur in Québec rural districts where the Dynaflect is used on old roads with a very variable or even unknown stratigraphy. As the interpretation of Dynaflect data depends on so many factors (1,6) and because there is no universal mean to achieve this goal, a useful procedure is to give to the user as much information and help as it is possible to do and let him decide in some circumstances where is the truth.

The pragmatic approach which is presented in this paper is knowledge based. It differs from the previous ones because of its qualitative nature. It tries to infer information from both classical methods as those briefly described before and from structured data collected from the past concerning deflection basins and soil samples. The main purposes of this system are to point out the differences which could exist between classifiers and to tell if a classifier agrees or not with the structural evaluation of a pavement given by soil samples that have been formerly associated with a given set of Dynaflect values. In doing this comparative evaluation on the spot, the system takes into account as much as possible the visual observations which it is able to suggest in order to eliminate some alternatives or to focus on a possible conclusion. These visual observations can be related to the aspect of the road or to the surrounding ground.

The system is composed of several parts: a road database, a set of statistical analysis results, a set of rules defining the classifiers and the conditions under which they can be used and the meta-rules integrating the whole and allowing the management of the system.

2. THE ROAD DATABASE

The database contains information from sixteen roads, the total length of which is about two hundred kilometers. These roads are located in the most densely populated area of Québec, spanning from the east to the west of the province. Since these roads are located in a rural environment , they do not have an important traffic load.

Two thirds of the roads considered in the study are built in a flat country and the remaining is hilly and cut by valleys. The nature of the soil is very diverse, sometimes swampy, sometimes rock based, sometimes it is clay or sand or gravel.

The sampling of the soil which has been made in these roads shows a very variable stratigraphy. The thickness of the bituminous layer can be as low as five centimeters or as high as forty centimeters. Usually it ranges between ten and twenty centimeters. The thickness of the foundation is between twenty-five centimeters and about one meter with a mean of seventy-five centimeters.

These different combinations induce a broad range of results from the Dynaflect. Before being stored in the database, these results are corrected for temperature variations according to the procedure defined in (7). The database contains as many as 3336 Dynaflect readings.

Along with the Dynaflect results, the database also includes soil samples taken in the same section as the Dynaflect measures. These samples give a very precise description of the structure of the pavement and the soil beneath up to three meters. More than four hundred of these samples are recorded in the database and can be related to corresponding Dynaflect readings.

2.1. The relational schema

The database is composed of two groups of relations. The first one is related to Dynaflect measures, the last one to soil samples. These two groups share a common relation:

- **road_descriptions** which contains the detailed description of the roads (reference number, name, number of traffic lanes,...) on which the measures or the sampling have been made.

2.1.1. The Dynaflect group of relations

The main relations of this group are:

- **Dynaflect_trials** which describes the general characteristics of a Dynaflect trial on a road section (trial reference number, road reference number, direction, location of the section, time, date, technician,...),

- **Dynaflect_readings** which contains the values given by the five geophones at a measure point during a Dynaflect trial on a road section and the characteristics associated with this reading (trial reference number, location of the measure point, geophone values, temperature, signature, soil sample reference number, ..).

2.1.2. The soil samples group

This group is linked to the preceding by the soil sample reference number. This attribute exists in the Dynaflect_readings relation and in the soil_samples relation described later. It is defined only when the Dynaflect reading and the soil sampling are located close enough to be associated with one another. This group is mainly composed of the relations:

- **soil_samples_sets** which describes sets of soil samples done on a section of a road (soil samples set reference number, road reference number, location of the section, date, equipment,...),

- **soil_samples** details the soil samples belonging to a set (soil samples set reference number, soil sample reference number, location of the sampling, depth compression code, thickness compression code,...),

- **soil_sampling_elements** gives the nature of each part of a soil sampling (soil sample reference number, depth, type of the part, category,...).

2.2. The compression of data

2.2.1. Compression of Dynaflect data, the geophone signature

The Dynaflect data have been compressed to give a geophone signature which is recorded in the relation **Dynaflect_readings.** To establish this signature the range of values generated by each geophone has been divided into 10 classes whose limits are given by the quantiles (order 10) calculated for each distribution. Thus, each value generated by a geophone can be coded in a digital form. The concatenation of these codes produces the desired signature. It represents in a very synthetic view the general aspect of the whole set of values. It can also be used to build a cluster of similar Dynaflect readings which can be composed of items presenting the same or very similar signatures. The corresponding attribute is indexed for a fast retrieval.

2.2.2. Compression of soil samples data

These very complex and diverse data have been interpreted in such a way that only certain elements have been retained. This way of synthesizing implies the loss of a certain amount of the qualitative information, but that is one way to build groups of samples.

Two techniques have been used:

- the first one considers the presence of certain materials at given depths,
- the second one considers only certain materials and takes into account the thickness of these materials.

Depth compression

The different materials that could be part of the structure of the pavement have been grouped in the following categories:

- bituminous mix labelled: "g",
- gravels (GW, GP, GM, GC or some combinations) labelled: "a",

- sands (SW, SP, SM, SC or some combinations) labelled: "b",
- inorganic clays or silts (CL, CH, ML, MH) labelled: "c",
- organic soils labelled (OL, OH): "d",
- very organic products such as PT labelled: "e",
- rock labelled: "f",
- other materials labelled: "h".

Since the Dynaflect response is sensitive to the surface course, it was decided to consider the thickness of this layer. Three boundary values (8cm, 11cm et 14cm) that correspond to the quartiles and to the median have been used to delimit four groups of width labelled "1" to "4". For the other materials only their presence at the following depths: 0.3m, 0.5m, 0.75m, 1m and 1.5m has been considered. Finally the presence or the absence of rock in the sample is denoted by "1" or "0". A sample with the following composition:

0.12 B.M (bituminous mix),

0.35 GP-GM (gravel),

0.40 SW-SM (sand),

1.10 PT (organic products),

2.30 SM (sand),

2.90 PT (organic products),

3.00 Rock,

is represented by the following depth compression code: "3aeeeb1". Such a code gives a rather accurate representation of the sample, but this degree of accuracy is, in some circumstances, too high to allow for proper statistical analysis. This drawback is mainly due to the lack of soil sampling data and it must be overcome by a different coding scheme.

Thickness compression

In that case, the data collected from the soil samples have been grouped into three categories: the bituminous mix, the gravels and the sands. For each of these layers, three types of thickness have been considered: small denoted by the symbol ".", medium ("o") and important ("O"). The boundary values used to delimit these classes are: 10 cm and 15 cm for the bituminous mix, 30 cm and 60 cm for the gravels and the sands. The nature of the infrastructure has been taken into account using a fourth symbol that can be "C" if some clay has been encountered or "F" if the presence of rock has been detected. The preceding soil sample is coded "o.OF" using this technique.

3. THE PAVEMENT CLASSIFIERS

Some classical systems, for the qualitative evaluation of pavements from Dynaflect measures, have been tested in order to see in what extent they can be used in the conditions of Québec old roads.

3.1 The testing sample

A testing sample was set up for this purpose during the 1989 summer. More than five hundred Dynaflect measures were performed on characteristic sections of roads chosen for their variety. This sample is quite representative of the various conditions under which the Dynaflect is used in Québec. It was also designed to achieve a direct correspondence between the soil samples already available on these sections and the Dynaflect measures. In the near vicinity of each soil sampling point, four Dynaflect measurements were realized. The median value was considered as the most representative one and was retained to reflect with enough accuracy the typical Dynaflect response at the sampling points. At the end of this process 116 couples (Dynaflect measures, soil samples) were so constituted.

3.2 The testing method

Data has been subdivided into several categories. These are based on elements which may induce significative differences in the behavior of the geophones (6):

- the presence of gravel or sand, clay or silt, rock and organic products in the basement of the road,

- the thickness of the bituminous layer.

Twelve categories have been set up accordingly:

	Clay or silt	Clay or silt and rock	Clay or silt and organic products	Gravel or sand	Gravel or sand and rock	Gravel or sand and organic products
BM < 15cm	category 1: size 41	2: 7	3: 4	4: 23	5: 17	6: 7
BM ≥ 15cm	7: 6	8: 0	9: 0	10: 2	11: 9	12: 0

The 116 couples have been distributed in these categories and three of them were found to contain no data (8,9 and 12).

The structural characteristics of the pavement have been summarized in a structural index:

$$SI = \text{Round}((2A + B + 0.4C) / 10)$$

where A is the thickness of the bituminous layer, B is the total thickness of gravel material and so for the factor C and the sand material.

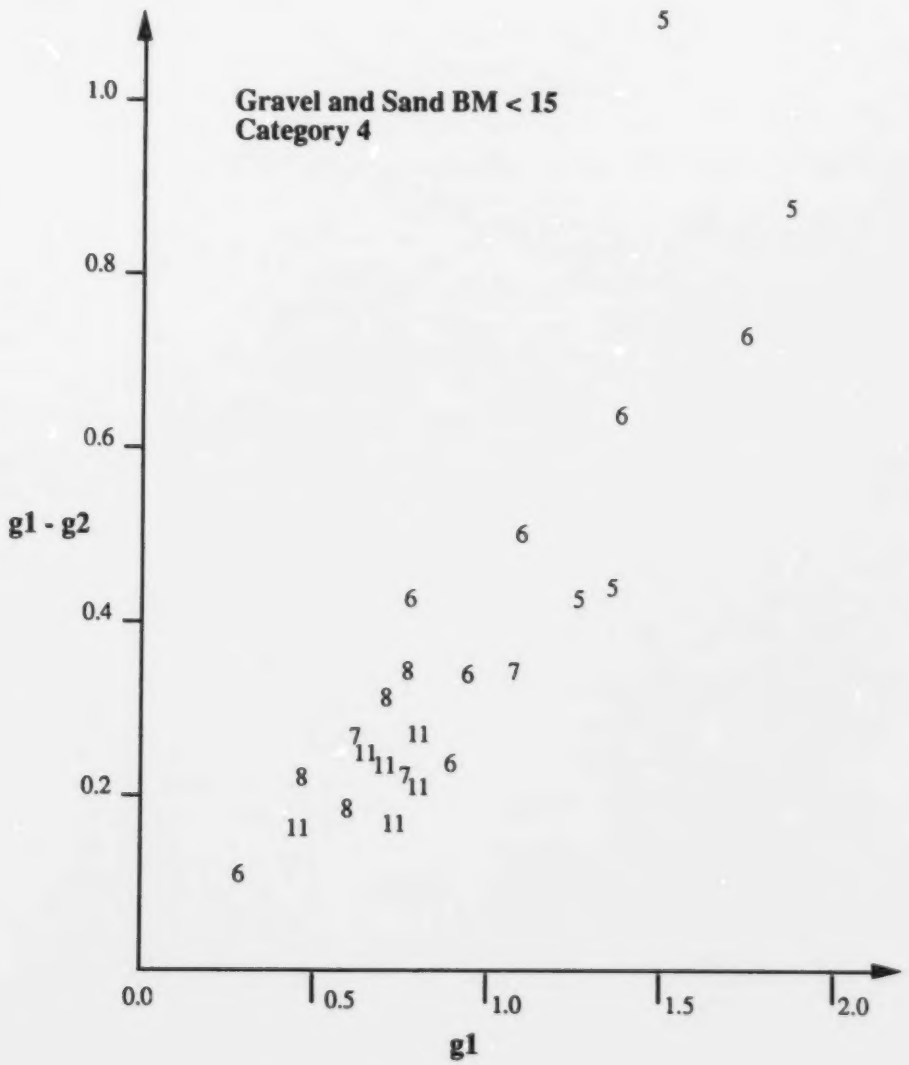
Three evaluation systems have been tested in each structural category using the sample of the 116 couples. A methodology which consists in figuring the structural coefficient of each couple in a

graphic was used in order to know the sensitivity of these evaluation systems in each case. These systems were:

- the Majidzadeh evaluation system (1), which uses the geophones 1 and 5,

- the Reinslett evaluation system (8), which uses g_1 and the Surface Curvature Index (g_1 - g_2),

- the basin surface evaluation system, which uses (g_4 - g_5) and a basin surface coefficient ($0.5\ (g_1 + 2g_2 + 2g_3 + 2g_4 - 7g_5)$)



This example shows what is the graphical display in the case of the structural category 4 and the Reinslett evaluation system. On this graphic, at the points corresponding to Dynaflect measurements, the associated structural index values have been indicated to reflect the accordance between these two sets of values.

3.3 The testing results

Results obtained tend to be in line with previous studies on Dynaflect measurements. The three classifiers tested showed consistency in grouping measurements made on different types of subgrades. However, discrimination was much better on sand and gravel than on clays and silts. Subgrades involving to some extent rock produced results that tend to concentrate around the origin of the axes of the classifiers. On the contrary, tests on organic subgrades showed much higher Dynaflect values.

Dispersion of values is more pronounced in the case of clay and silt subgrades. Structural equivalence indices in those cases have been associated with lower as well as higher Dynaflect values, probably reflecting a wide variation of in situ clays and silts. Nevertheless, structural equivalence indices were well discriminated in the case of gravel and sand subgrades, with higher indices being closer to the origin of the axes of the classifiers.

Variation of results reflects to a large extent variation in pavement structures typical of older rural highways that were part of this study sample. It will be worthwhile to repeat the study using samples from more recently constructed highways involving greater standardization in their pavement structures.

4. WHAT DOES THE SYSTEM DO ?

The system can be used in real time, during a campaign of Dynaflect measures, or later, to perform a better analysis without being restricted to time considerations. However there is no specific delimitation between what can be done on the spot and what must be delayed. Depending on the

amount of time available between two Dynaflect readings, more or less can be performed, the more being the better in order to take a maximum benefit of the visual observations that can be done. All the results are stored in a temporary database build up on the model of the permanent one. They can be easily retrieved for a further investigation.

Roughly speaking the system performs two main tasks:

- the creation and the update of the temporary part of the database used for the storage of the Dynaflect measures made during a campaign,
- a qualitative evaluation at each measure point of the results given by the Dynaflect.

The temporary part of the database consists of relations built on the model of the Dynaflect group of relations. It is used to collect all the information introduced during a session of measurements. It can be incorporated in the permanent part after a validation phase occurring later. The corresponding elements mainly consist of answers to queries given by the system and calibrated values produced by the geophones. The evaluation of the results is meant to give the user a qualitative appreciation of the pavement if the system has enough elements or at least a set of possible structural compositions based on past results extracted from the database.

At the beginning of a campaign of measurements on a road section some pieces of information are asked from the user:

- the calibration factor for the Dynaflect which is going to be used,
- the location of the road section on which the measures are going to be done,...

This information is stored in the temporary relation Temp_Dynaflect_trials.

4.1 Before the measurement

Before a measurement some observations are entered in the system:

- visual observations on the aspect of the pavement such as the presence and the severity of cracks (this information can be used by the system to verify if the conditions under which the Dynaflect can be used are fully respected),

- the temperature,
- the exact location of the measure,...

4.2 After the measurement

The geophone results are transmitted in real time by a serial line to the computer where they are corrected and calibrated. The geophone signature is calculated. These data, as well as the pieces of information gathered before, define a "tuple" which is inserted in the temporary relation Temp_Dynaflect_readings.

Some other questions are asked to the user in order to determine the category the portion of the road located nearby the measure point belongs to:

- the probable configuration of the subgrade (rock, sand or gravel, clay, organic products),
- the probable thickness of the bituminous mix (thin or thick),...

These observations as well as the visual aspect of the road are stored in a special relation in tuples linked to the corresponding reading tuple in the relation Temp_Dynaflect_readings.

If the answers are precise enough, that is if their associated coefficients of certainty are high, it is then possible to use the appropriate classifiers and, if they all agree, to obtain directly a qualitative evaluation of the pavement. In the other cases, another strategy has to be used.

4.3 The structural profiles association process

At first this process consists in searching in the database for signatures similar to the one corresponding to the Dynaflect measures. The similarity can be exact in the best case or loose. In that case the selected signature can differ from one unity in one position from the new one. The main characteristics of the measure points, as they are recorded in the database for the similar geophone signatures, are presented to the user. The output mainly consists of a list of the homogeneous road sections on which the analogous measures have been obtained. The operator has then the opportunity to validate the selection made by the system. He can, for example,

eliminate the readings done on road sections that do not seem to suit according to his experience and his visual observation about the present situation. The final selection is recorded in a special link relation in order to be used later. For each validated geophone signature the system tries next to retrieve, if they exist in the database, the associated soil sample using the link defined by the attribute "soil sample reference number" in the Dynaflect_readings relation. If possible, another selection is made automatically according to the answers given with regards to the probable configuration of the subgrade or the thickness of the bituminous mix. The set of corresponding sample signatures are presented to the user depending on their category. In each of these categories the corresponding structural signatures are summarized in the form of a regular expression.

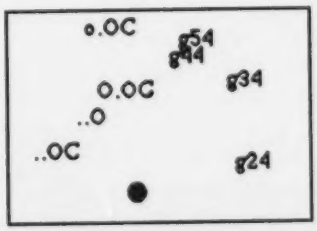
	Clay or silt	Clay or silt and rock	Clay or silt and organic material	Gravel or sand	Gravel or sand and rock	Gravel or sand and organic material
BM < 15cm	1aaccc0		1abbbc0	2aaaab0		
BM ≥ 15cm	4bb[bc]cc0		4bbbbc0	4bbbbb0		

At the end of this process the user has the opportunity to query the database in order to fetch the detailed soil sample readings which can be associated with the selected structural signatures. He has also the opportunity to eliminate some of these signatures if they do not seem to correspond to configuration at the measure point.

In the case where no similar signature can be found or where no soil sample can be associated due to the actual lack of data, the system can use a set of statistical results to determine the nearest depth structural profiles. These profiles of the type ".oOF" have been associated with geophone classes of responses (g21 is for example the first class for the geophone two, that is the one with the smallest values). The degree of correspondence between a depth structural profile and a geophone class of response is given by the number of time this geophone class of response can be associated

with this type of profile. The associations are the ones that are recorded in the database between a geophone point of measure and a soil sampling point. Such an association only exists if the distance between these two points is small enough (10 meters in case of a rocky subgrade). The corresponding array of correspondence has been processed by the correspondence factorial analysis method in order to have an Euclidean representation of the proximities between the structural profiles and the geophone classes. In this representation a depth structural profile point is located in a geophone space at a position which depends on the degree of the associations observed with the geophone classes. If a structural profile has been, comparatively to the others, more often associated with a geophone class, it is so located in the Euclidean representation near this class (see (6) for a more detailed explanation). For each new Dynaflect set of results, it is then possible to compute what are the nearest structural profiles. They are the one which are the closest from that new point.

The following graphic gives an illustration of the method. It shows, in the Euclidean representation given by the correspondence analysis, the proximity between the new Dynaflect measurement represented as a big dot (●) and the nearest structural profiles.



This computation of distances can be realized in a short time so that the user can react in real time to the choices given to him by this component of the system.

5. CONCLUSION

This knowledge based system has been developed on a Compaq SLT/286 portable personal computer with the Arity Prolog package. This package comprise all the tools needed in the software implementation of the project:

- a SQL interface to manage the relational base of facts containing all the data,

- a Prolog interpreter and compiler with an expert system shell for the development of the knowledge base,

- an embedded C and bridges to other classical programming languages for the computations which have to be made such as the distance computations.

The system is under is final phase of development which will end in December 1990. At that time, it will be tested in laboratory before being used in real time conditions on roads. However, as all experts systems, it is not intended to remain in a frozen state at the end of the testing phase. The evaluation strategy will certainly improve in the future as soon as new data will become available. This kind of update is allowed and easy to do in such a context because of the high level expression of this strategy as it has been implemented by rules and meta rules in a knowledge base. The manual interventions of the user which are actually needed due to the lack of information, should be reduced with a better understanding of the behavior of the system. This will make the decision process faster and safer and the system will react with a greater uniformity than it presently does because of these manual interventions.

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